Demonstration of Capability to Simulate Particle Irregular Shape and Poly-Disperse Mixtures Within Lunar Lander Plume-Surface Interaction

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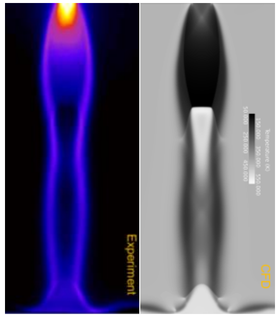
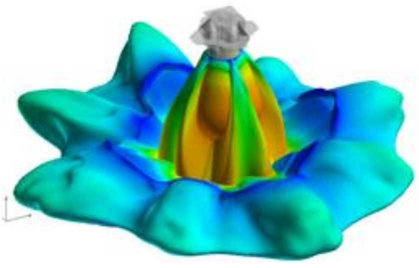
PSI NASA Game Changing Development Multi-Year Project

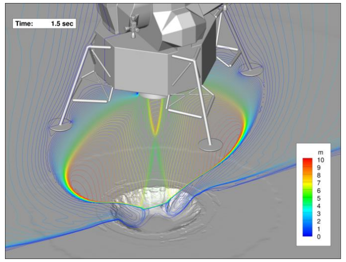
Objective: Develop an integrated modeling, simulation, instrumentation capability, and testing approach to predict propulsive landing Plume-Surface Interaction (PSI) effects

Predictive Simulation Capability

- Developing PSI modeling and simulation capability for full-scale Moon and Mars vehicles
  - Plume physics
  - Erosion/cratering physics
  - Ejecta dynamics

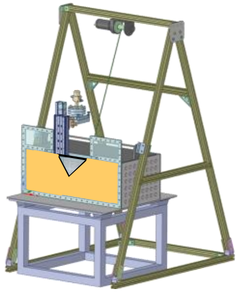


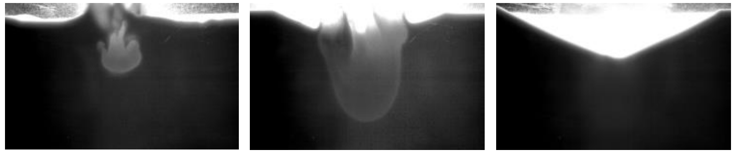




Ground Testing

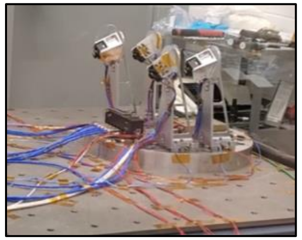
- Subscale, inert gas, supersonic cratering test in MSFC TS300 vacuum facility, CY21/22
- Hot-fire cratering tests planned with Robotic-Scale lander engine and Human-Scale lander engine at MSFC TS300 and GRC Plumbrook Station
- Novel test techniques and diagnostics for Lunar and Mars relevant environments

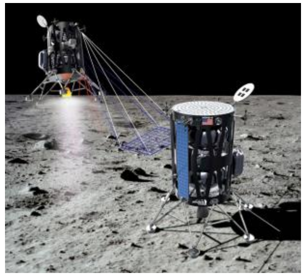




Flight-Focused Instrumentation

- Design/Development completed, with validation and testing underway:
  - Millimeter Wave Doppler Radar (MWDR)
  - SCALPSS stereo camera (2021 flight on Nova-C CLPS lunar lander)
  - Dust Concentration Monitor (DCM)

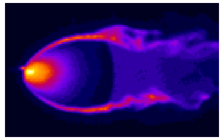




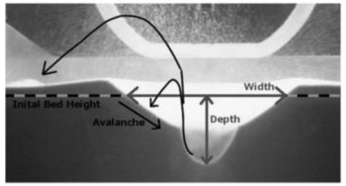
PSI – Predictive Simulation Capability (PSC) Development

FOUR SPECIFIC TASKS were defined for the **<u>Predictive Simulation Capability (PSC)</u>** Development element of the PSI Project sponsored by NASA Game Changing Development (GCD).

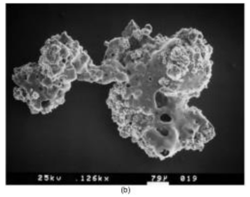
- **Task 1 – Plume Flow in Low-Pressure/Vacuum Environments**
  - ➢ Accurately model plume expansion, dynamics, and impingement in Martian and Lunar low-pressure/vacuum environments



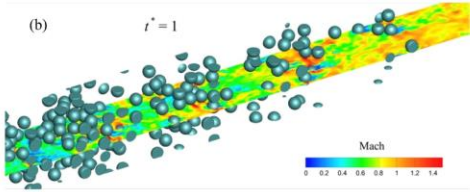
- **Task 2 – Effect of Plume Flow on Crater Development and Ejecta Sheets**
  - ➢ Simulate complete range of soil material erosion and fluidization mechanism with gas-particle two-phase simulations to accurately predict crater shape and size



- **Task 3 – Regolith Particle Phase Modeling**
  - ➢ Refine soil mixture particle-particle interaction modeling to capture extreme cohesiveness of irregular shape, poly-disperse lunar regolith



- **Task 4 – Gas-Particle Interaction Modeling**
  - ➢ Close fundamental modeling gaps for gas-particle interaction in supersonic ejecta streams and clouds



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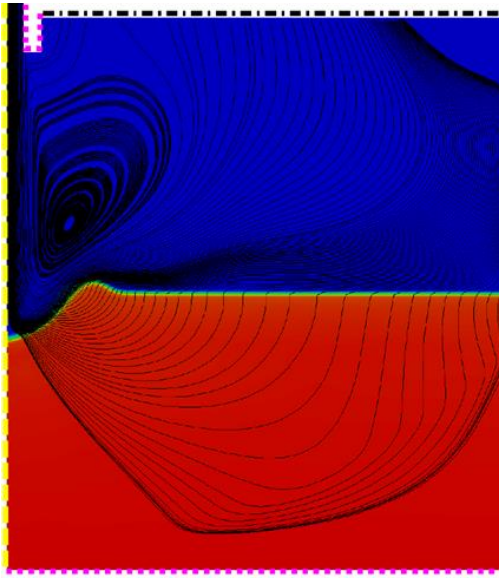
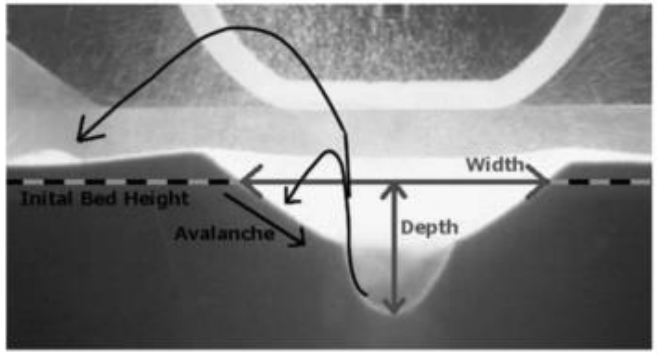
Gas-Granular Flow Solver (GGFS)
Simulation of Crater Development and Ejecta Sheets

Gas-Granular Flow Solver (GGFS): Gas-Particle Two-Phase Simulations

- **GGFS** features Eulerian-Eulerian modeling approach, treating both gas and granular material as mixing continuum phases. Directly computes the interaction of gas and granular phases and simulate erosion, cratering and ejecta processes.
- GGFS has been ported to highly scalable Loci framework under PSI project. **Loci/GGFS** enables NASA project applications on HPC supercomputer assets.
- Eulerian particle phase modeling avoids modeling of intractable number of individual particle interactions. Requires constitutive closure models (stress, dissipation, friction, drag, …) in governing equations.
- Particle Kinetic Theory can be applied for sphere closure models.
- Closure models for non-spherical particles are generated from small-scale detailed DEM simulations.
- The Eulerian-Eulerian gas/granular flow solution framework is then applied to efficiently simulate the gas-granular multi-phase flow.





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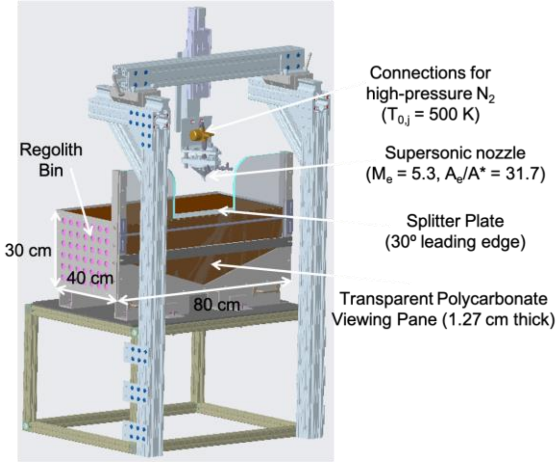
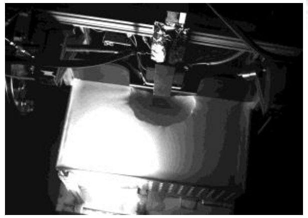
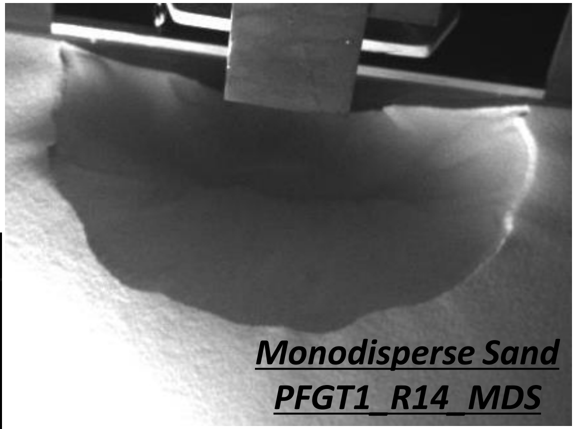
Influence of Particle Shape and Mixture in Realistic Environment

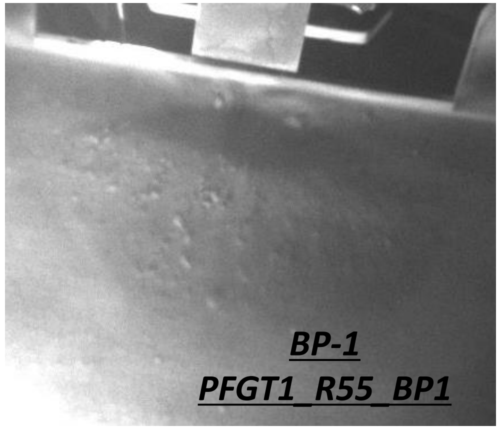
- PFGT-1: Physics Focused Ground Test – MSFC TS300 Vacuum Chamber – FY21
  - ➢ Scaled supersonic plume impingement at Martian and near-Lunar background pressures
  - ➢ Six simulants: Glass spheres, mono- and bi-disperse sand, sieved BP-1, tri-disperse mix, full BP-1
  - ➢ Progression in simulant complexity designed to provide validation for irregular particle and poly-dispersity effects Loci/GGFS models
- Example shown below: P=0.053 torr, h/D=10
- Dramatic difference in crater characteristics between mono-disperse sand particles and full composition BP-1 poly-disperse irregular particle mix







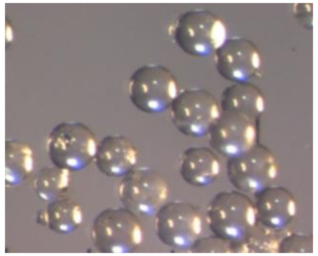
Monodisperse Sand
PFGT1_R14_MDS



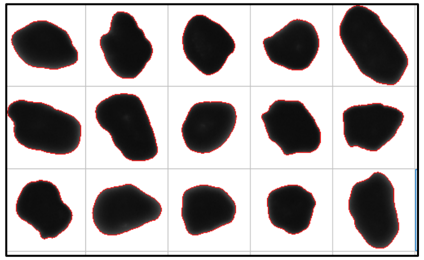
BP-1
PFGT1_R55_BP1

Realistic Modeling Of Poly-disperse Soil Composition with Irregular Shape Particles Is First Order Requirement

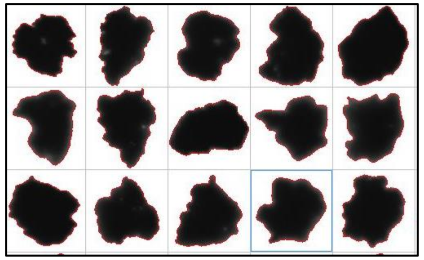
PFGT-1 Pre-Test Simulant Particle Scans



PFGT-1 Simulant: Glass Spheres



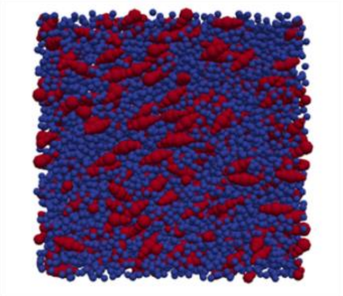
PFGT-1 Simulant: Quartz Sand
Irregular, sub-rounded/sub-angular

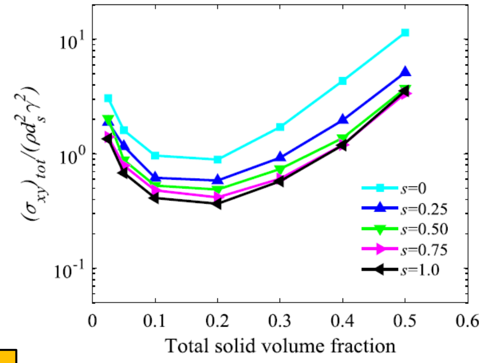


PFGT-1 Simulant: BP-1
Irregular, sub-angular/angular

Particle Phase Property Modeling Capabilities in Loci/GGFS

- Loci/GGFS particle mixture modeling framework designed to accommodate mono-disperse and poly-disperse mixtures of ideal (spherical) and irregular particle shapes
- Lunar regolith mixture may require databases with N=8+ discrete particle size bins
- **Spherical Particles – Particle Kinetic Theory**
  - Spherical shapes use particle kinetic theory closure model formulations
  - Poly-disperse mixture: Garzo-Hrenya-Dufty (GHD) mixture property model
  - GHD solves coupled set of equations for mixture property using particle kinetic theory for each species in mixture. Recent Loci code optimizations have led to orders of magnitude speed-up.
- **Irregularly Shaped Particles – DEM based database generation with runtime interpolation**
  - Particle shape and angular features modeled with sphere clumps. DEM particle-particle interaction performed to extract properties (stress, dissipation, …). Use Python scripted parametric LIGGGHTS DEM database generation.
  - Tabular datasets accessed by Loci/GGFS during execution.
  - Previously limited to bi-disperse data sets. Efficient Loci 2-D interpolation modules were readily available. Recent extension to general Loci N-dimensional interpolation modules.





Poly-disperse composition

Focus of this Presentation is on Capabilities of GHD Based Spherical Shape Modeling

Garzo, V., J. Dufty, C. Hrenya, “Enskog theory for polydisperse granular mixtures I: Navier-Stokes order transport”, Phys. Rev. E. 76 (2007)
Garzo, V., C. Hrenya, J Dufty, “Enskog theory for polydisperse granular mixtures II: Sonine polynomial approximation”, Phys. Rev. E. 76 (2007)
Murray, J.A., Benyahia, S., Metzger, P., Hrenya, C. M., “Continuum representation of a continuous size distribution of particles engaged in rapid granular flow”, Physics of Fluids 24, (2012).

Application Demonstration of Loci/GGFS
Particle Shape and Mixture Effects on Apollo LM Surface Cratering

- Loci/GGFS overall maturation has reached level that warrants evaluation of available soil modeling options for a full-scale relevant scenario
- Selected Apollo Lunar Module terminal landing phase PSI cratering -- quasi-steady simulation

- **Demonstration served multiple purposes:**
  - Simulation in near-vacuum environments - test robustness of two-phase flow solver for simulations on edge of continuum flow with orders of magnitude range between gas and particle densities
  - Assess and demonstrate capabilities and robustness of currently available particle model implementation In GGFS
  - Demonstrate ability to predict effects postulated as first order: irregular shape and poly-dispersity
  - Application readiness: Identify computational cost drivers for timely large scale computational modeling for customer support

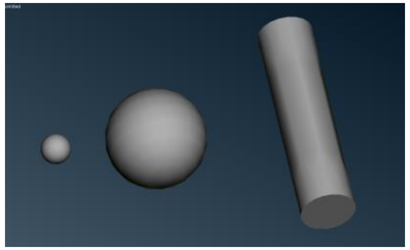
Application Demonstration of Loci/GGFS

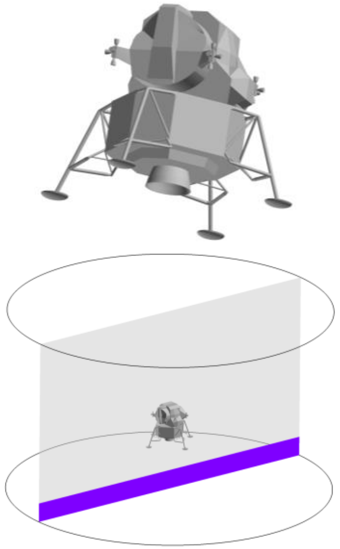
Particle Shape and Mixture Effects on Apollo LM Surface Cratering

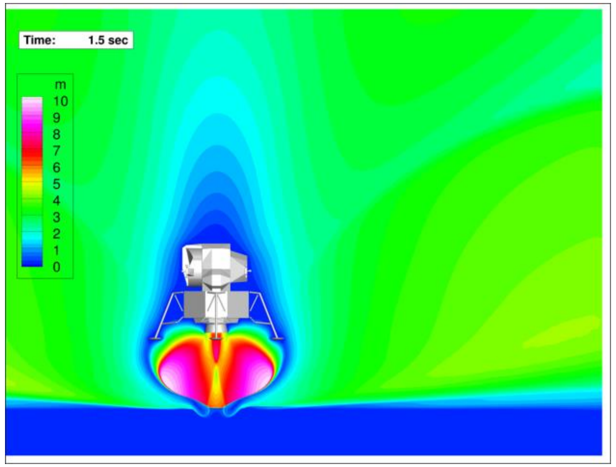
- Apollo Lunar Module full scale geometry model
- Elevation 5m from soil surface to engine exit
- Engines throttled to 2200 lbf
- Farfield pressure set to 0.1 Pa (Near Lunar)

<u>Assessed particle shape and mixture effects with four models:</u>

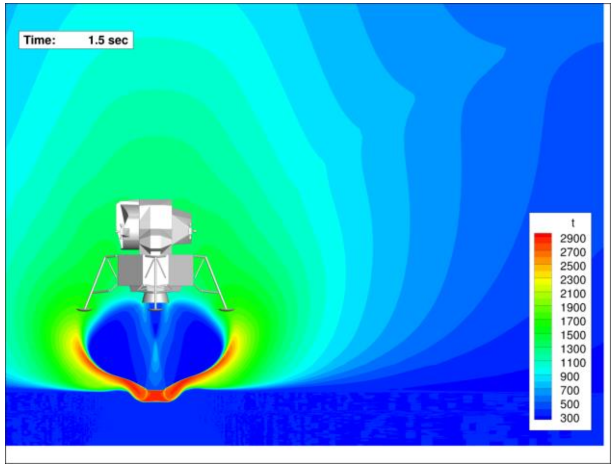
- Single size spherical particles, D=30 micron, D=100 micron
- Bi-disperse spherical particles, D=30+100 micron
- Single size irregular particle shape, Cylinder AR=4 with volume equivalent to 100 micron
- Tri-disperse spherical particles, D=10+30+100 micron



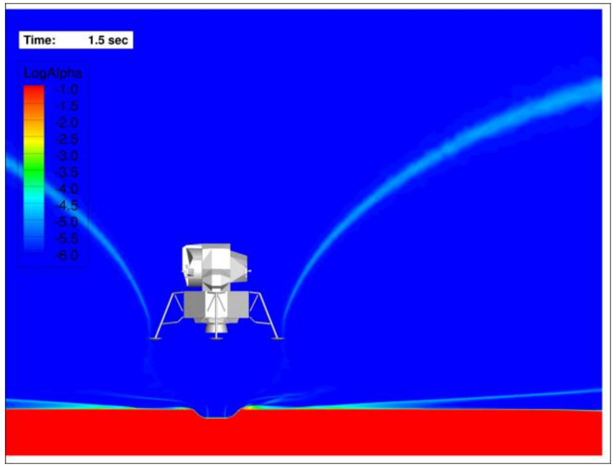




Mach Number



Temperature

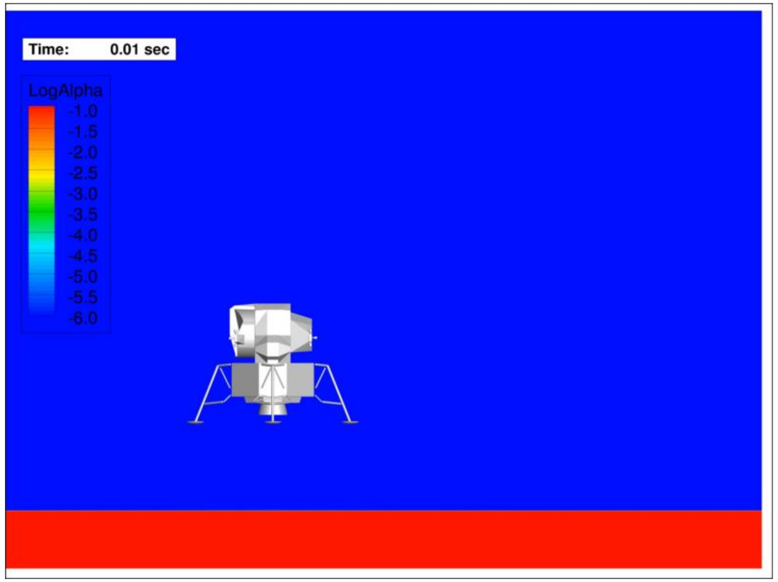


Particle Volume Fraction (log10)

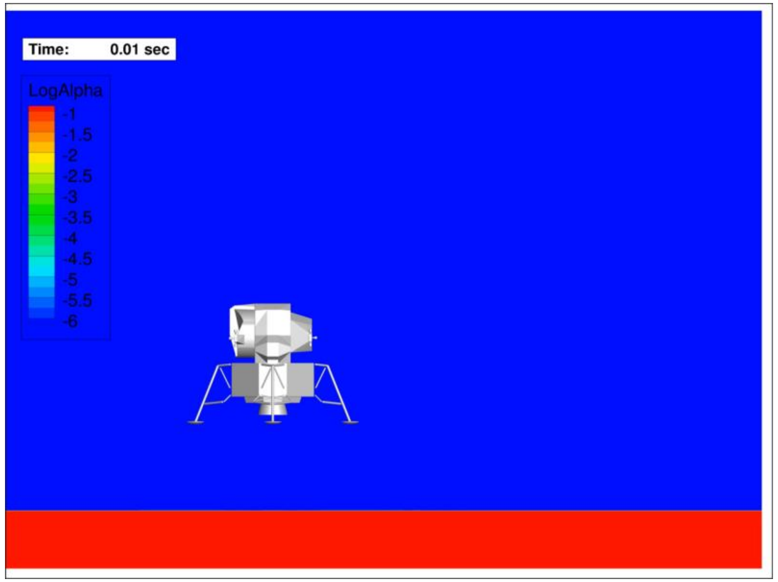
Ejecta Sheet Evolution: Effects of Poly-dispersity

- Initial stir-up of particles from impulsive plume startup and impingement on soil slowly rising up as farfield flow forms
- Near surface ejecta sheet forming from soil surface outside of crater ; ejecta sheet angle ~ 5-10deg
- Secondary ejecta stream ejected from crater edge
- Poly-disperse mixture composition results in wider spread of eject sheets

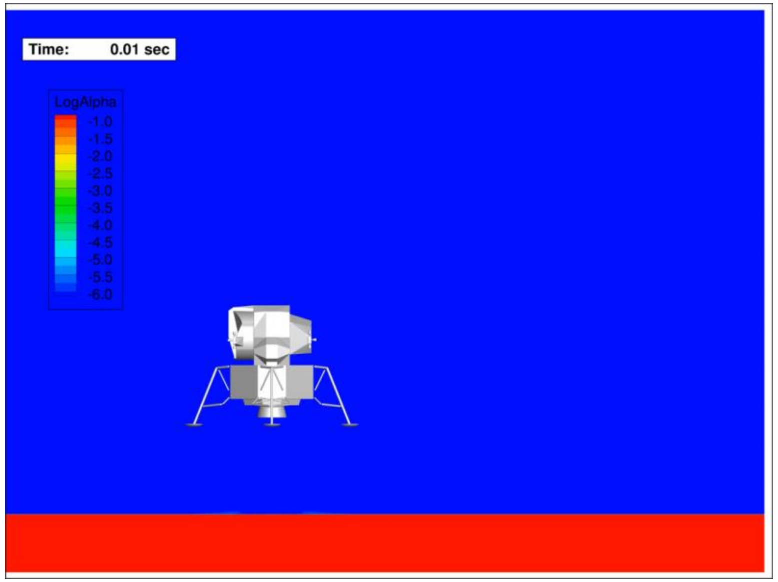
Mono-disperse 100mi spheres



Bi-disperse 30-100mi spheres



Tri-disperse 10-30-100mi spheres

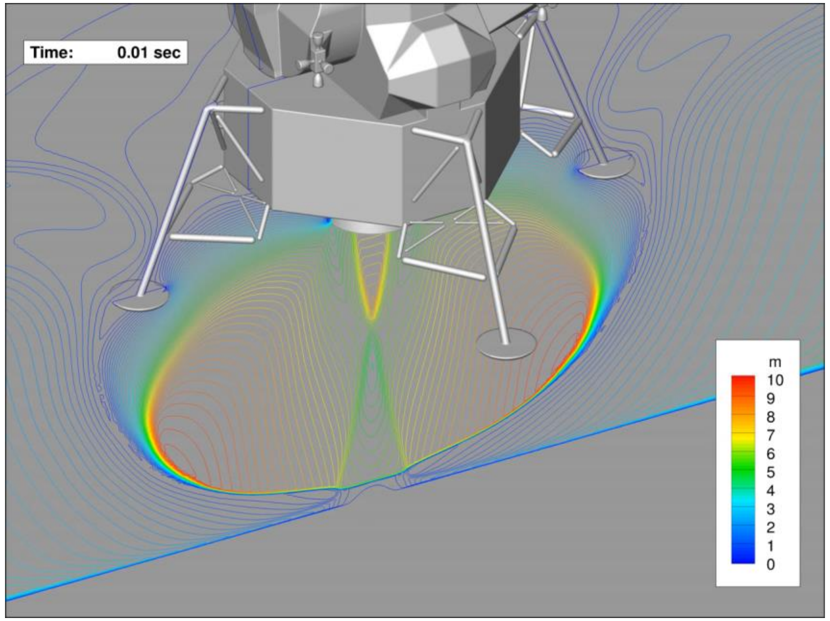


Animations

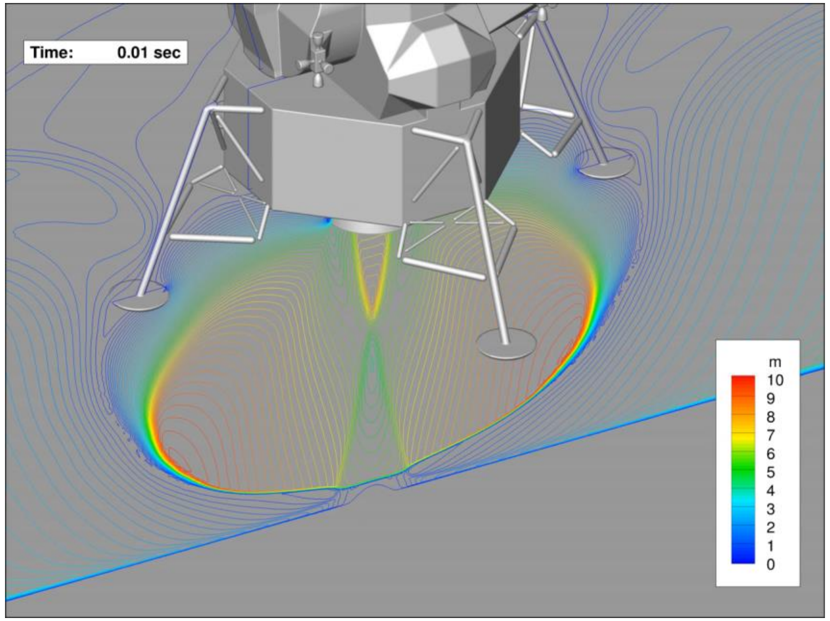
Plume Dynamics and Crater Evolution

- Poly-disperse mixtures result in progressively shallower crater
- Noticeable increase in surface erosion effects outside of crater

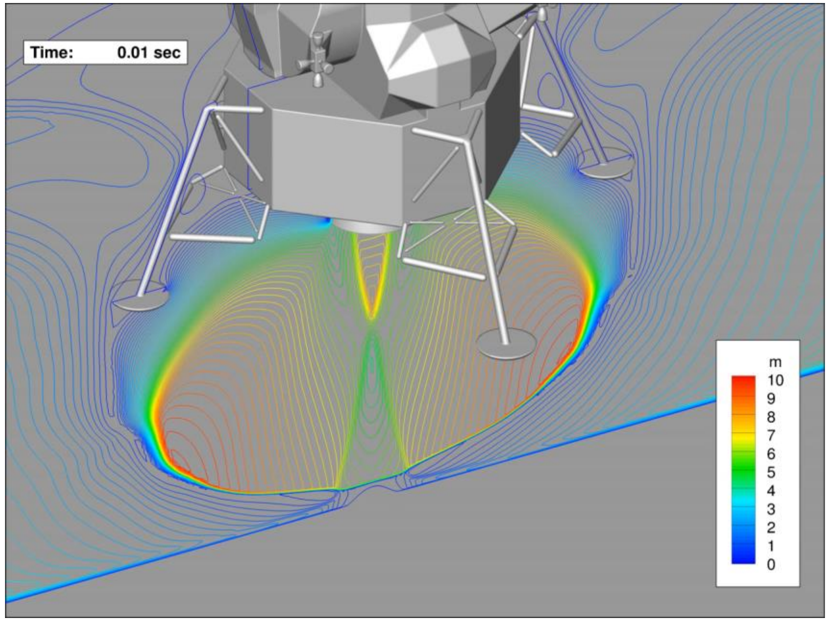
Mono-disperse 100mi spheres



Bi-disperse 30-100mi spheres



Tri-disperse 10-30-100mi spheres



Animations

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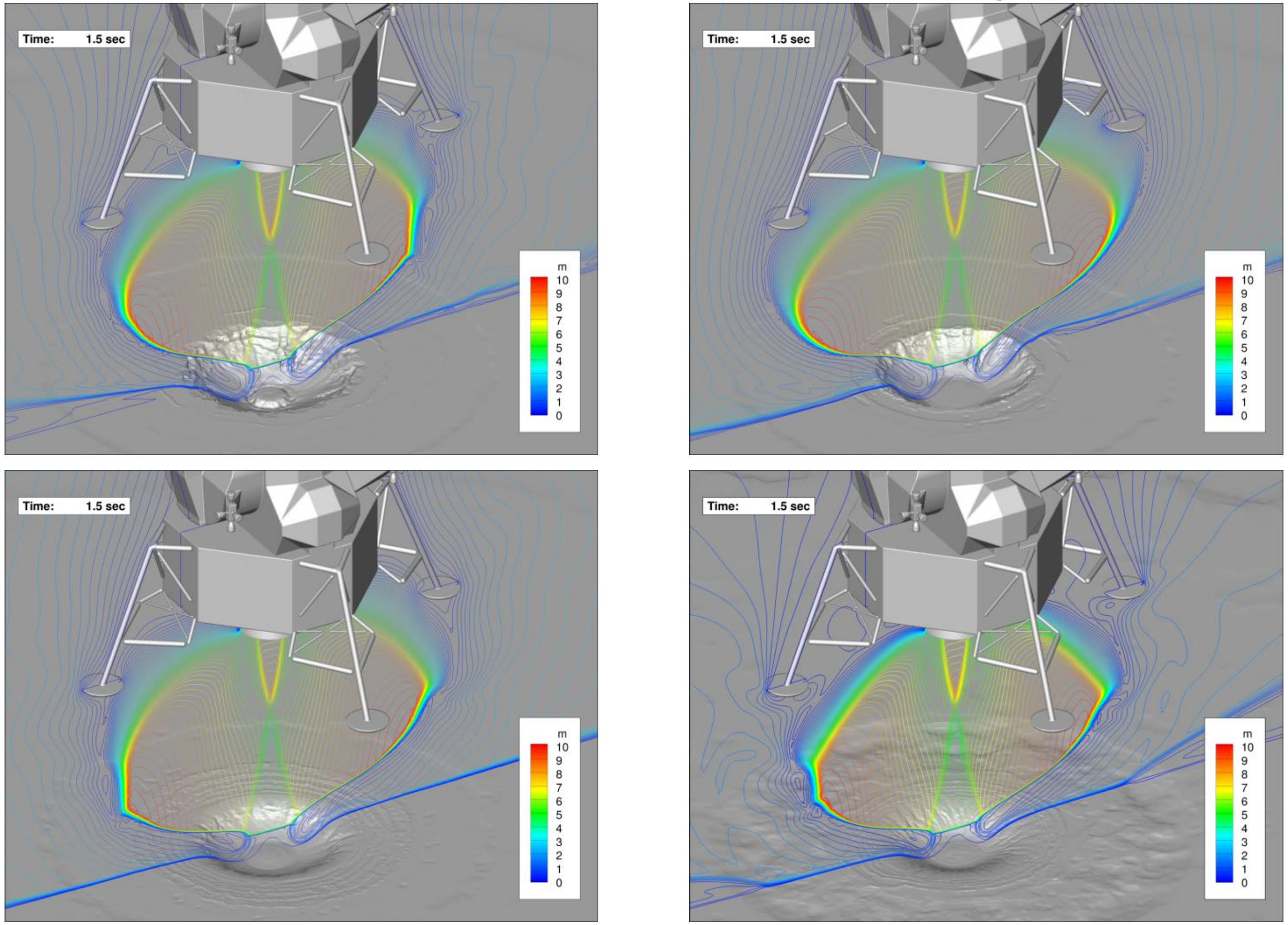
Effect of Particle Mixture on Crater Shape/Depth

- Comparison of crater shape shown at t=1.5 sec
- Continuous reduction in crater depth with poly-dispersity
- More pronounced surface erosion effects outside of crater for tri-dispersed

Loci/GGFS Simulations Capture Crater Characteristics Expected For Particle Size, Shape And Mixture Effects.

30mi spheres | ***100mi spheres***

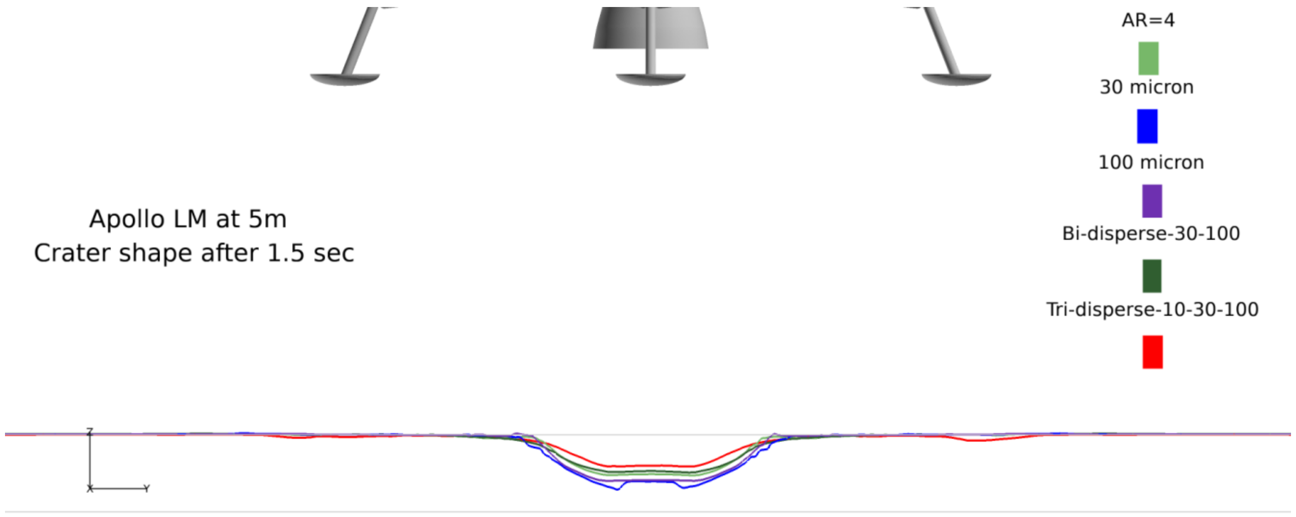


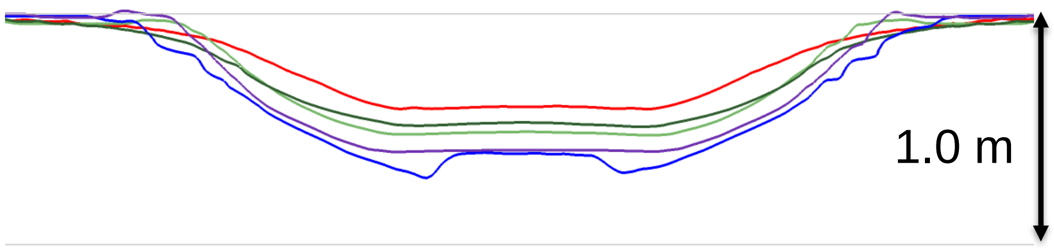
Bi-disperse 30-100mi spheres | ***Tri-disperse 10-30-100mi spheres***

Effect of Particle Shape/Mixture on Crater Depth

- Crater depth profile comparison shown at t=1.5 sec
- Continuous reduction in crater depth with poly-dispersity
- Started next level simulation with N=4 for analytical GHD sphere model (10-30-100-300 micron)
- Further poly-dispersity effects assessment will begin using results of DEM modeling

Results Obtained To Date Indicate That Increased Poly-dispersity Results In Increased Resistance To Erosion And Reduction In Crater Depth





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Computational Speed-up for Production Applications

- Simulations currently require 3 weeks+ ; Cost scales with number of particle bins in poly-disperse modeling
- This is too slow to satisfy customer needs in project support production application
- Loci/GGFS implemented in Loci highly scalable, rule based computational framework. Current Loci/GGFS version constitutes robust implementation of all features.
- Entered next phase focusing on algorithm optimization on all levels - already demonstrating significant improvements. Solution of two-phase gas-granular mixture models present numerous occurrences of stiff, high-gradient coupled algorithms.
- Graphical Processing Units (GPU) were recognized as providing potential for significant computational speed increases, in particular for large number of repetitive granular phase sub-models and mixture computations.
- Heterogenous implementation (GPU/CPU) could provide significant speed-up. A Loci-based mini-application for GPU execution was funded by a NASA HPC Modernization Effort and completed in early FY21—results indicated significant acceleration of Loci/GGFS and Loci-base CFD tools in general were likely.
- This will require funding not allocated under the PSI GCD project.

Conclusion

- Presented application demonstration of Loci/GGFS capabilities for Apollo Lunar Module PSI surface cratering.
- Demonstrated capabilities and robustness of currently available particle models In GGFS
- Results obtained to date indicate that increased poly-dispersity results in increased resistance to erosion and continuous reduction in crater depth
- Future simulations will begin using DEM based models to assess cost and scaling. For irregular shapes, database lookup is the only way to perform poly-disperse simulations.